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HIGH-RISE EVACUATION MODELING - DATA AND APPLICATIONS

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ABSTRACT

A model called EXIT89 has been developed at NFPA to simulate the evacuation of a large building, with the capability of tracking each occupant individually. The output of this model, in combination with a fire and smoke movement model using the same building layout, can be used to predict the effects of cumulative exposure to the toxic environment present in a structure fire. The capability of modeling the presence of disabled occupants has recently been added to the model. Data to test and enhance the model was obtained from fire drills conducted in office buildings in the U.S. and U.K., as well as evacuations involving able-bodied and disabled subjects in a hotel.

1. MODEL DESCRIPTION

EXIT89 requires as input a network description of the building, geometrical data for each room and for openings between rooms, the number of occupants located at each node throughout the building, and smoke data if the effect of smoke blockages is to be considered. The user is allowed to select among several options, including whether the occupants of the building will follow shortest paths out of the building or will use familiar routes; whether smoke data, if any, comes from a fire and smoke model or will be input as blockages by the user; whether there are any delays in evacuation throughout the building; whether there are any additional delays in evacuation among the occupants of the building and, if so, what percentage of the occupants will delay and what are the minimum and maximum delay times; and whether any of the occupants are disabled and if so, at what percentage of "normal" speed each disabled person will travel.

The following is a brief overview of the model. It either calculates the shortest route from each building location to a location of safety (usually outside) or sets user-defined routes through the building. It moves people along the calculated or defined routes until a location is blocked by smoke. Affected exit routes are recalculated and people movement continues until the next blockage occurs or until everyone who can escape has reached the outside.

Evacuation can begin for all occupants at time 0 or can be delayed. Additional delays over a specified range of time can be randomly assigned to occupants. Smoke data can be used to predict when the activation of a smoke detector would occur and evacuation will begin then or after some user-defined delay beyond that time. The program is written in FORTRAN and currently runs in mainframe and PC versions.

2. USER OPTIONS

There are six options set by the user at the beginning of the input file. The first indicates whether metric or standard measurements will be used in input and output. Internally, all calculations are done in metric scale but this option allows the simple use of evacuation data and floor plans from a variety of sources. The second option specifies the body size used as the basis of density calculations that are used to calculate velocities. These choices are described in more detail in a later section. The third option allows the user to specify whether occupants will be moving at emergency or normal (slower) speeds. This also is described more fully later.

The fourth option allows the user to determine whether the program should calculate the shortest paths between nodes or whether the user will be specifying the node to which occupants will move from each node. If the user selects specified routes, the node to which occupants of a node will move is included as part of the node description in the input. User-specified paths will be used until a node on a floor becomes blocked by smoke. In that case, the routes for the floor will be recalculated using the shortest-route routine.

The fifth option indicates whether or not the user is reading in smoke data from CFAST or whether there will be user-defined blockages or no blockages. And finally, the user selects full output, which prints information every time someone moves from one space to another, or summary output showing floor and stairway clearing times and usage of exits.

On the next two lines, the user indicates whether or not additional delay times should be randomly distributed among the occupants. If yes, the user then specifies for what percentage of the occupants there will be additional delays and over what range of time (in seconds) those delays should be chosen.

3. CALCULATING WALKING SPEEDS

EXIT89 uses walking speeds calculated as a function of density based on formulas from Predtechenskii and Milinskii. [1] Their formula for density of a stream of people, D, is:

$$D = Nf/wL \quad (m^2/m^2) \tag{1}$$

where
- N = number of people in the stream
- f = the area of horizontal projection of a person
- w = width of the stream
- L = length of the stream.

Their model established an optimal density of 0.92. Although a higher density can be observed in real situations, 0.92 is the maximum they used in empirical expressions for walking speeds. Based on their observations, they developed the following equations for normal circumstances. For the mean values of velocity as a function of density for horizontal paths:

$$V = 112\,D^4 - 380\,D^3 + 434\,D^2 - 217\,D + 57 \quad (m/min) \tag{2}$$

for $0 < D \leq 0.92$.

For movement through doors

$$V_o = Vm_o \quad \text{(m/min)} \tag{3}$$

$$\text{where } m_o = 1.17 + 0.13 \sin (6.03D_o - 0.12)$$

For movement down stairs

$$V_\varnothing = Vm_\varnothing \quad \text{(m/min)} \tag{4}$$

$$\text{where } m_\varnothing = 0.775 + 0.44\, e^{-0.39D_\varnothing} \cdot \sin (5.16\, D_\varnothing - 0.224)$$

Since the model does not yet move people up stairs, the values for travel up stairs are not shown.

In emergencies, such as earthquakes or fire, the fear that makes people try to flee danger raises the speed of movement at the same densities. Predtechenskii and Milinskii found the following relationship between the two velocities:

$$V_e = \mu_e \cdot v \tag{5}$$

where $\mu_e = 1.49 - 0.36\,D$ for horizontal paths and through openings
$\mu_e = 1.21$ for descending stairs.

Tables of velocities by density were given for normal, emergency and comfortable movement along horizontal paths, through openings and on stairs. EXIT89 currently incorporates the velocities for normal and emergency movement.

Queueing is handled by the decreased walking speeds that result from increased densities as more occupants move into a room or stairway. The program does not currently allow occupants to select less crowded routes; they simply join the queue at nodes along the shortest route.

4. BODY SIZE DATA

Predtechenskii and Milinskii's work used body sizes calculated from the measurements of Soviet subjects. The area of horizontal projection of a person used in these calculations is 0.113 m^2 (1.22 ft^2) -- the mean dimensions of an adult in mid-season street dress. Subsequent work by Ezel Kendik using Austrian subjects found significant differences in the results. [2] The value of 0.113 m^2 described above compares to the Austrian result for subjects between the ages of 10 and 15 years without coats. The value for Austrian subjects between ages 15 and 30 wearing coats was 0.1862 m^2 and without coats was 0.1458 m^2. The value for adults over age 30 without coats was 0.1740 m^2.

A table of mean body dimensions representative of U.S. male and female workers between 18 and 45 years of age was obtained from *Occupational Safety and Health in Business and Industry*. Based on this data, an "American" value for horizontal projection of a person of 0.0906 m^2 was calculated, far smaller than that calculated for Soviet or Austrian subjects. The choice among the three sets of data is an input option set by the user.

5. MODELING PRESENCE OF DISABLED OCCUPANTS

The presence of disabled people during an evacuation is a feature recently added to EXIT89. The strategy chosen at this time assumes, as demonstrated in work by the University of Ulster, that the presence of disabled occupants does not impede able-bodied occupants. [3]

The user specifies how many of the occupants at a node are "disabled." This can mean not only how many will evacuate slower than the average occupant, but also any able-bodied people who will evacuate with someone who is disabled. People with disabilities include those whose travel speed is slowed by the use of a walker, wheelchair or age, as well as small children and those who will accompany them.

If a node has any disabled occupants, the user enters on the next line the proportion of "normal" speed at which that person will move. For example, if a disabled person moves at three-quarters of the speed of an able-bodied person, the user enters 0.75 as the speed factor for that person.

This method of handling disabled occupants assumes that their presence does not impede the able-bodied occupants. The densities used to calculate travel speeds for able-bodied occupants count all occupants of a node and treat them as if they were all of the same body size. This does not account for the size of wheelchairs or the space taken up by walkers and strollers, for instance. The justification for this assumption is based on the evacuations studied by the University of Ulster that showed that the presence of people in wheelchairs or with walkers did not affect the travel speed of other occupants.

By using this feature, people moving at more rapid than normal speeds can also be modeled by identifying them as "disabled" but setting their speed factors at some value greater than 1.0.

6. EXAMPLE 1 - RANDOMLY DISTRIBUTED DELAY TIMES

A series of evacuations were conducted by the University of Ulster to test the effect of disabled persons on occupant flow in mixed ability populations. Three of these evacuations took place in a hotel with two daytime scenarios and one nighttime scenario. The night and one of the day scenarios used the same fire location and these were the two evacuations for which EXIT89 was run.

The hotel wing used for the evacuation was a two-story structure with exit stairs at both ends and another stairwell in the center. One of the end stairs was made unavailable for the evacuation. Several of the occupants taking part in the evacuation were disabled. They included users of wheelchairs, canes and walkers. Disabled occupants were not included in this first set of example runs.

In the course of the actual evacuations, alarm bells did not consistently ring throughout the bedroom section of the hotel. In the first example, the alarm was inaudible for many of the occupants, significantly delaying their evacuation. In the second example, the alarm was at least slightly audible for all occupants.

The initial locations of the occupants for each of the evacuation exercises were provided on floor plans. Also available were the length of time it took occupants to leave their rooms and their time to leave the building. The location of cameras through the building allowed researchers to determine the duration and causes of additional delays during evacuation.

In the first daytime scenario, estimated delays in evacuating bedrooms ranged from one to 30 seconds. In addition, 14 out of 27 occupants observed by cameras delayed at some point in the corridors during their evacuation. The duration and reasons for these delays were detailed in the report. The reasons included, among others, stopping to read a notice on the foyer door (one to two second delay), holding doors open for wheelchair users (nine to 13 second delay), calling on friends (up to 30 second delay) and traveling in the opposite direction of designated escape route (up to nine second delay).

Among the 22 non-disabled occupants observed by cameras in this evacuation, the times to reach the exit ranged from 16.6 to 60.0 seconds with a mean time of 37.1 seconds. The first run of this evacuation used reported and estimated delay times in the rooms for these occupants and resulted in evacuation times that ranged from 23.1 to 60.1 seconds with a mean time of 39.5 seconds. A second run of this evacuation added random delays of one to 30 seconds to half of the occupants. In this case, the predicted evacuation times ranged from 23.1 to 79.1 seconds with a mean time of 45.8 seconds. A closer look at the movement of the occupants showed that many of the occupants actually reached the exit sooner because the delays reduced congestion in the corridors and allowed them freer and more rapid movement. Since most of the reported delays during evacuation actually lasted less than 10 seconds, the example was run a third time with random delays of one to 10 seconds distributed among half the occupants. This resulted in predicted evacuation times that ranged from 23.1 to 65.8 seconds with a mean time of 41.8 seconds.

In the nighttime scenario, observations were provided for 55 non-disabled occupants. For these people, estimated delays in evacuating bedrooms ranged from five to 78 seconds. In addition, 33 of these 55 occupants were observed to delay in the corridors during their evacuation. These delays ranged from one to 15 seconds and were due to making decisions, queueing, and assimilating information.

Among these 55 occupants, the times to reach the exit ranged from 17.3 to 90.0 seconds with a mean time of 42.6 seconds. The first run of this evacuation used reported and estimated delay times in the rooms for these occupants and resulted in evacuation times that ranged from 24.9 to 107.8 seconds with a mean time of 50.1 seconds. A second run of this evacuation added random delays of one to 15 seconds to 60 percent of the occupants. In this case, the predicted evacuation times ranged from 27.1 to 116.3 seconds with a mean time of 56.0 seconds. Since most of the reported delays during evacuation actually lasted less than five seconds, the example was run a third time with random delays of one to five seconds distributed among 60 percent of the occupants. This resulted in predicted evacuation times that ranged from 27.7 to 110.9 seconds with a mean time of 52.3 seconds.

In both of the actual evacuations, disabled occupants were present; however, it was found that they did not adversely impact the movement of the non-disabled evacuees.

7. EXAMPLE 2 - ADDING DISABLED OCCUPANTS

Building on the final results of Example 1, four disabled occupants were added to the modeled population. There were actually five disabled occupants in the real evacuation, but travel speed was not available for one of the wheelchair occupants. Two wheelchair occupants traveled at speeds close to the average for able-bodied occupants (1.15 m/s vs. 1.52 m/s). The other two disabled occupants were a wheelchair user who traveled at about one-eighth of the average speed of the able-bodied occupants, as a result of impedance from a walker user who traveled at about one-fifteenth of the average speed of the able-bodied occupants.

The model was rerun with these four disabled occupants added. As was observed in the actual evacuation, there was no effect on the travel times of the able-bodied evacuees. The travel times observed in the actual evacuation for these four people were 51.0 seconds, 56.9 seconds, 174.0 seconds and 222.0 seconds. The times estimated for them in the model were 58.0 seconds, 61.7 seconds, 182.3 seconds and 295.4 seconds, respectively.

8. CONCLUSION

The model in its current form does not include any explicit behavioral considerations but it does allow behavioral considerations to be handled implicitly by incorporating time to perform investigation activities or to alert others before evacuating in the delay times that the user specifies for the occupants of each node. In addition to specifying delay times for each location, the user now can also have the computer randomly assign additional delays to some percentage of the individuals throughout the building. In this same way, another behavior that can be dealt with implicitly is the tendency of able-bodied adults in the presence of other able-bodied adults to ignore early warnings of the presence of a fire.

EXIT89 now allows the user to model the frequently observed tendency of occupants to follow the route out of the building that they are most familiar with, not the shortest paths out of building which often would involve the use of emergency exits. These familiar paths defined by the user will remain in place until a location on that floor becomes blocked by smoke and the routes on that floor need to be recalculated using the shortest route algorithm. The model now also allows the simulation of disabled people, who can be incorporated using slower walking speeds.

Walking speeds in the model are calculated as a function of densities and are based on tables of values from Predtechenskii and Milinskii. The model does not yet simulate crawling through smoky rooms by reducing walking speeds, or reversing direction where possible to use a less smoky, though longer escape route.

One of the program's inputs is the capacity of nodes. The reason for including this value was to allow evacuees to avoid nodes that were already crowded if alternate routes are available. This would prevent occupants from queueing at one stairway while the other section or sections of the floor emptied out into less busy stairways. Refinements of the program to define and possibly limit the range of a smoke detector also need to be added to the model.

Future plans for the model include documenting observed travel speeds and the delay times that can be used for occupants to begin evacuation and for delays during evacuation. These travel speeds and delay times may be occupancy-specific. Testing of the model using data from actual emergency and non-emergency evacuations will also continue. A PC-version of the model will be tested during the Fall of 1995.

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Discussion

Edward Zukoski: How does a person in a wheelchair get down from the second floor to the ground floor?

Rita Fahy: They don't, and that's one of things that I hadn't put in. They should be heading to areas of refuge (safety). Which means that every floor should have a location that functions like the outside. The people in the examples were all on the first floor.

Masahiro Morita: When the fire is expanding and if you are in the hallway and there's no smoke, it's hard to know in which direction that people would go. Then, as the fire progresses, chances are that the path would vary. How did you take care of that when you input the data?

Discussion cont.

Rita Fahy: First, everyone in one room will travel to the next room, but if the user decides to set the routes themselves, those would be the expected travel routes. We would probably all leave this building that way because that's the way we came in. Even if the user determines the routes, once blockage occurs and the routes are recalculated, they're recalculated using the shortest route algorithm.

Howard Baum: How much of the building or the room geometry is actually used in calculating these delay times? If the room has an unusual shape or if there's a major chunk of furniture in the room or if there's a zigzag in a hall, does that enter into the calculations?

Rita Fahy: There are two things going on there, the delay time is set by the user, and that's reaction time if you were doing an office evaluation. For instance, there may be some shut down procedure that people would have to do. The accounting department can't just get up and leave, so that's delay time, and that's set by the user. The evacuation distance is measured from the center of the space. The speed is calculated using the densities based on the usable floor area. So if there's a complicated geometry within the room, that's not addressed directly.

Howard Emmons: The real problem seems to be what you talked about plus the fact that the fire is growing at the same time and maybe even faster than the people are going out. Have you coupled this with a fire model to take this into account? And if not, do you have plans to do so?

Rita Fahy: The only way the model deals with the fire is when it's coupled with the smoke model. If rooms are blocked as people are evacuating, they are trapped. It's up to the next model to "kill" them. It also doesn't take into consideration the actions of the people and what they can do to affect smoke and fire spread by opening and closing doors, things like that.

Pravinray Gandhi: It looks like a lot of the data that you have may be interpreted in a probabilistic manner. Are you thinking of adding that complexity in your model to make it more probabilistic by introducing distribution functions for people movement and so forth?

Rita Fahy: There are some types of real behavior that it would be really hard to model, like back and forth sorts of things. I would like to have it be more probabilistic, but I would want there to be some data from real life, otherwise, it would add complexity without being defensible.